Higgs mass implications on the stability of the electroweak vacuum

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Abstract

We update instability and metastability bounds of the Standard Model electroweak vacuum in view of the recent ATLAS and CMS Higgs results. For a Higgs mass in the range 124–126 GeV, and for the current central values of the top mass and strong coupling constant, the Higgs potential develops an instability around 10¹¹ GeV, with a lifetime much longer than the age of the Universe. However, taking into account theoretical and experimental errors, stability up to the Planck scale cannot be excluded. Stability at finite temperature implies an upper bound on the reheat temperature after inflation, which depends critically on the precise values of the Higgs and top masses. A Higgs mass in the range 124–126 GeV is compatible with very high values of the reheating temperature, without conflict with mechanisms of baryogenesis such as leptogenesis. We derive an upper bound on the mass of heavy right-handed neutrinos by requiring that their Yukawa couplings do not destabilize the Higgs potential.

1 Introduction

Experimental data recently reported by the LHC experiments after the analysis of their 5/fb dataset restrict the Standard Model (SM) Higgs boson mass to be in the range 115 GeV $< m_h < 131$ GeV (ATLAS [1]) and $m_h < 127$ GeV (CMS [2]), with a first hint in the mass window 124 GeV $< m_h < 126$ GeV. Such a light Higgs is in good agreement with the indirect indications derived from electroweak precisions constraints [3] under the hypothesis of negligible

contributions of physics beyond the SM. Moreover, no clear signal of non-SM physics has emerged yet from collider searches.

Motivated by this experimental situation, we present here a detailed investigation about the stability of the Standard Model vacuum under the hypothesis 124 GeV $< m_h <$ 126 GeV, assuming the validity of the SM up to very high energy scales.

Despite the fact that there is no evidence for physics beyond the Standard Model (SM) from the LHC, the experimental information on the Higgs mass gives us useful hints on the structure of the theory at very short distances, thanks to the sizable logarithmic variation of the Higgs quartic coupling at high energies. For instance, the recent LHC results can be used to constrain the scale of supersymmetry breaking, even when this scale is far beyond the TeV range [4]. Another consideration is that, for low enough values of m_h , the Higgs potential can develop an instability at high field values, signaling an unambiguous inconsistency of the model at very short distances [5, 7–15].

In this paper, we reconsider the instability and metastability bounds. Then we study the implication of these results on information about the early stages of the Universe. If the Universe spent a period of its evolution in the presence of a hot thermal plasma, the absence of excessive thermal Higgs field fluctuations, which might destabilize our present vacuum, imposes an upper bound on the reheat temperature after inflation, generically denoted by $T_{\rm RH}$. This upper bound has implications for the dynamics of the evolution of the Universe and for the creation of the observed baryon asymmetry. In particular, these considerations become relevant in the case of leptogenesis (for a review see Ref. [16, 17]), in which the decays of heavy right-handed (RH) neutrinos are responsible for the generation of a lepton asymmetry, eventually leading to a baryon asymmetry. Depending on the mass of the RH neutrinos, the leptogenesis scenario might require relatively high values of the reheating temperature.

The presence of massive RH neutrinos has also a direct impact on the structure of the Higgs potential at high energies, and thus on the stability bounds, via one-loop corrections induced by the RH neutrino Yukawa couplings. Independently on any consideration of leptogenesis or reheating temperature, the requirement that the electroweak vacuum has a lifetime longer than the age of the Universe implies an interesting upper bound on the mass of the RH neutrinos, as a function of the physical neutrino mass. We derive this limit assuming that the SM and the RH neutrinos describe all the degrees of freedom up to a very large energy scale, close to the Planck mass.

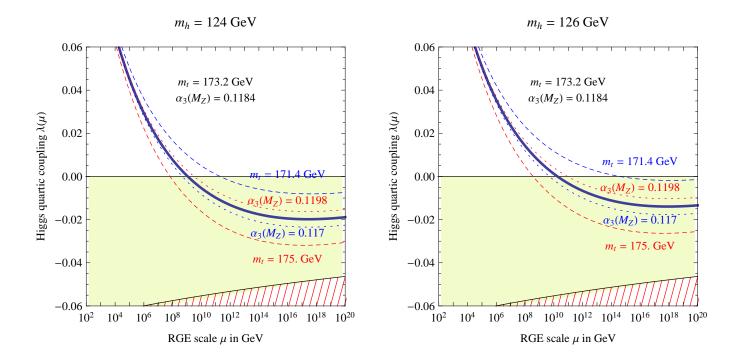


Figure 1: RG evolution of the Higgs self coupling, for different Higgs masses for the central value of m_t and α_s , as well as for $\pm 2\sigma$ variations of m_t (dashed lines) and α_s (dotted lines). For negative values of λ , the life-time of the SM vacuum due to quantum tunneling at zero temperature is longer than the age of the Universe as long as λ remains above the region shaded in red, which takes into account the finite corrections to the effective bounce action renormalised at the same scale as λ (see [11] for more details).

2 Stability and metastability bounds

We first present the analysis on the Higgs instability region at zero temperature. We are concerned with large field field values and therefore it is adequate to neglect the Higgs mass term and to approximate the potential of the real field h contained in the Higgs doublet $H = (0, v + h/\sqrt{2})$ as

$$V = \lambda(|H|^2 - v^2)^2 \approx \frac{\lambda}{4}h^4 \ . \tag{1}$$

Here v = 174 GeV and the physical Higgs mass is $m_h = 2v\sqrt{\lambda}$ at tree level. Our study here follows previous state-of-the-art analyses (see in particular [9, 11, 12]). We assume negligible corrections to the Higgs effective potential from physics beyond the SM up to energy scales of the order of the Planck mass. We include two-loop renormalization-group (RG) equations for all the SM couplings, and all the known finite one and two-loop corrections in the relations between

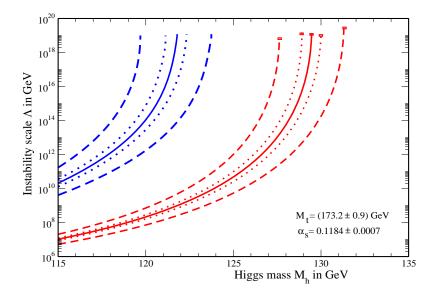


Figure 2: The scale Λ at which the SM Higgs potential becomes negative as a function of the Higgs mass for the central value of m_t and α_s (plain red), as well as for $\pm 2\sigma$ variations of m_t (dashed red) and α_s (dotted red). The blue lines on the left are the metastability bounds (plain blue: central values of m_t and α_s ; dashed blue: $\pm 2\sigma$ variations of m_t). The theoretical error in the determination of the instability scale is not shown.

 λ and the top Yukawa coupling (y_t) to m_t and m_h .¹ Working at this order, we obtain a two-loop renormalization-group improved Higgs potential. Similarly, the effective action relevant to vacuum decay is computed at next-to-leading order in all the relevant SM couplings, including the gravitational coupling [12]. The main novelty of our analysis of the bounds is the use of the recent experimental information on the Higgs mass and of the updated values of the top mass and strong couplings:

$$m_t = (173.2 \pm 0.9) \,\text{GeV} \, [18], \qquad \alpha_s(M_Z) = 0.1184 \pm 0.0007 \, [19] \,.$$
 (2)

In fig. 1 we show the quartic Higgs coupling renormalized at high scales in the $\overline{\rm MS}$ scheme. We see that for $m_h = 124~(126)~{\rm GeV}$ and for the best-fit values of m_t and of α_s , the coupling becomes negative around $10^9~(10^{10})~{\rm GeV}$ (continuous line). However, this scale can be shifted by orders of magnitude by varying m_t within its uncertainty band: the red (blue) dashed lines show the effect of increasing (decreasing) m_t by two standard deviations. In particular, reducing m_t by two standard deviations allows to avoid the instability for $m_h = 126~{\rm GeV}$.

¹In particular, we include one-loop electroweak corrections in the determination of $\lambda(m_t)$ and $y_t(m_t)$, as well as two-loop QCD corrections in the determination of $y_t(m_t)$.

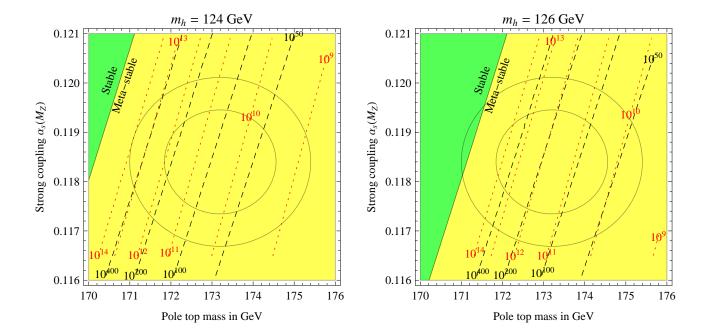


Figure 3: Measured values of the top mass and of the strong coupling at 68, 95% C.L. (2 dof) compared to the regions of the parameter space which are stable (upper-left, shaded in green) and meta-stable (yellow). In the latter case, the dashed curves are the iso-contours of the lifetime in years, and the dotted curves are the iso-contours of the instability scale in GeV. The theoretical error, estimated to be ± 3 GeV in m_h at fixed m_t , is not shown.

Furthermore, the red (blue) dotted lines show the effect of increasing (decreasing) α_s by two standard deviations, which has a smaller impact.

The instability scale Λ of the Higgs potential, defined as the Higgs vev at which the one-loop effective potential turns negative, is shown in fig. 2, (lowest red curves). This scale takes into account additional finite one-loop corrections [9] and is typically at least one order of magnitude above the scale at which $\lambda(\mu) = 0$. The lines in fig. 2 end at the scale at which the new minimum of the Higgs potential characterized by a large vacuum expectation value becomes degenerate with the electroweak one.

Fig. 3 shows the boundary between stability (green) and meta-stability (yellow) regions for fixed values of the Higgs mass, and as a function of the top mass and of the strong coupling. The condition for stability can be approximated as

$$m_h > 130 \,\text{GeV} + 1.8 \,\text{GeV} \left(\frac{m_t - 173.2 \,\text{GeV}}{0.9 \,\text{GeV}}\right) - 0.5 \,\text{GeV} \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3 \,\text{GeV} , (3)$$

where the error of 3 GeV is an estimate of unknown higher-order effects.²

² The theoretical errors in eqs. (3) and (4) are dominated by the uncertainties in the determination of $\lambda(m_t)$

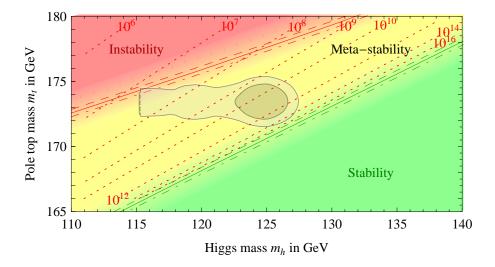


Figure 4: Measured value of the top mass and preferred range of m_h , compared to the regions corresponding to absolute stability, meta-stability and instability of the SM vacuum. The three boundaries lines corresponds to $\alpha_s(M_Z) = 0.1184 \pm 0.0007$, and the grading of the colors indicates the size of the theoretical errors. The dotted contour-lines show the instability scale Λ in GeV assuming $\alpha_s(M_Z) = 0.1184$.

Data indicate that we live close to this boundary, which corresponds to the intriguing possibility of a vanishing Higgs coupling (and perhaps also its beta function) at the Planck scale — a possibility discussed in previous papers with different motivations, see e.g. [12,21–25]. Note however, that the present experimental situation is only marginally compatible with the realization of such scenario. If there is indeed a potential instability below the Planck scale, the minimal scenario of Higgs inflation [26] (which already suffered from a unitarity/naturalness problem [27]) cannot be realized and one would be lead to nonminimal options that should cure, not only the unitarity problem [28] but also the instability (a potential threat to scenarios such as those proposed in ref. [29]).

2.1 Meta-stability

The fact that the Higgs potential develops a new deeper minimum does not necessarily mean that the situation is inconsistent, because our Universe could live in a metastable vacuum. As shown in fig. 1, the evolution of λ for $124\,\mathrm{GeV} < m_h < 126\,\mathrm{GeV}$ is such that it never becomes too negative, resulting in a very small probability of quantum tunneling. Updating

and $y_t(m_t)$ in terms of m_h , m_t and the other SM couplings. In particular, the leading error is induced by the unknown two-loop finite corrections in the determination of $\lambda(m_t)$. Estimating the size of these effects by varying the matching scale on $\lambda(\mu)$ in the range $m_t/2 < \mu < 2m_t$ leads to ± 2 GeV in m_h . The ± 0.5 GeV theoretical error [20] in the relation between the measured value of m_t and $y_t(m_t)$ leads to an additional ± 1 GeV. Summing linearly these two errors leads to the final error in eqs. (3) and (4).

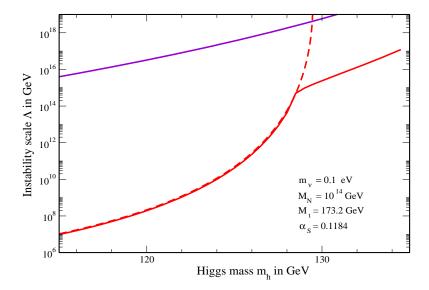


Figure 5: Stability bound for $m_t = 173.2$ GeV and $\alpha_s(M_Z) = 0.1184$ with (solid red) and without (dashed red) right-handed neutrinos at $M_N = 10^{14}$ GeV implementing a seesaw mechanism with $m_{\nu} = 0.1$ eV. The purple line corresponds to the metastability bound against vacuum decay by quantum tunneling in the presence of such see-saw. (The corresponding limit without right-handed neutrino effects lies below the LEP limit on the Higgs mass.)

our previous analyses, we find that the lifetime of the electroweak vacuum is longer than the age of the Universe for

$$m_h > 111 \,\text{GeV} + 2.8 \,\text{GeV} \left(\frac{m_t - 173.2 \,\text{GeV}}{0.9 \,\text{GeV}}\right) - 0.9 \,\text{GeV} \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3 \,\text{GeV} \ .$$
 (4)

The regions of stability, metastability, and instability in the m_h - m_t plane are illustrated in fig. 4. As can be seen, present data strongly favor metastability, although full stability is still allowed. In the metastable case, the expected lifetime of the SM vacuum, depending on the precise values of m_t and α_s , for two representative values of m_h , is reported in fig. 3.

These considerations clearly show the importance of future precise determinations of the top and Higgs masses that can be achieved at the LHC, together with higher-order theoretical computations.

2.2 Bounds on right-handed neutrinos

The presence of heavy right-handed neutrino states N in addition to the SM particle content

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{N}\partial N + y_{\nu}LHN + \frac{M_N}{2}N^2 + \text{h.c.}$$
 (5)

is well-motivated by the lightness of the left-handed neutrinos through the see-saw mechanism,

$$m_{\nu} = v^2 y_{\nu} \cdot M_N^{-1} \cdot y_{\nu}^T \ . \tag{6}$$

Therefore it is interesting to analyze the impact of the RH neutrinos on the instability region of the Higgs sector [37]. In view of eq. (6) the Yukawa couplings y_{ν} of the right-handed neutrinos are sizable if right-handed neutrinos are heavy, and they affect the RG evolution of the quartic higgs coupling making λ more negative at large scales μ above M_N :

$$(4\pi)^2 \frac{d\lambda}{d\ln\mu} = -2\operatorname{Tr} y_{\nu} y_{\nu}^{\dagger} y_{\nu} y_{\nu}^{\dagger} - 6y_t^4 + \frac{3}{8} \left[2g^4 + (g^2 + g'^2)^2 \right] + \mathcal{O}(\lambda). \tag{7}$$

We use the full two-loop RG equations, and we assume three degenerate right-handed neutrinos at the mass M_N with equal couplings y_{ν} which give three degenerate left-handed neutrinos at mass $m_{\nu} = y_{\nu}v^2/M_N$. This is a plausible assumption as long as neutrino masses are larger that the observed atmospheric neutrino mass difference $(\Delta m_{\rm atm}^2)^{1/2} \approx 0.05 \,\text{eV}$. Cosmological observations set an upper bound on m_{ν} of about 0.5 eV [17].

The effect of heavy right-handed neutrinos on the instability and metastability scales is illustrated in fig. 5 for one particular choice of parameters. In fig. 6 we show the upper bound on M_N obtained imposing that the lifetime of the SM vacuum exceeds the age of the universe. The bound ranges from $M_N < 10^{14} \,\text{GeV}$ for $m_\nu \approx 0.05 \,\text{eV}$ to $M_N < 10^{13} \,\text{GeV}$ for $m_\nu \approx 1 \,\text{eV}$, with a weak dependence on the Higgs mass within its favored range. The stability bound roughly corresponds to $y_\nu < 0.5$ and is therefore stronger than the perturbativity bound.

We stress that this bound holds only if RH neutrinos are the only new degrees of freedom appearing below the (high) energy scale where λ turns negative. One can indeed consider also additional degrees of freedom that could contribute keeping $\lambda > 0$. The best motivated case is, of course, supersymmetry, which ensures $\lambda > 0$ by relating it to gauge couplings and, moreover, makes technically natural the hierarchy between the electroweak and see-saw scales [38]. Two additional examples are i) extra quartic couplings of the form $S^2|H|^2$, where S is a new light scalar which could be the Dark Matter particle, that would contribute positively to eq. (7); ii) extra weak-multiplets around the electroweak scale (e.g. Dark Matter multiplets [6]), which increase the value of g, g' at higher scales, indirectly giving a positive contribution to eq. (7).

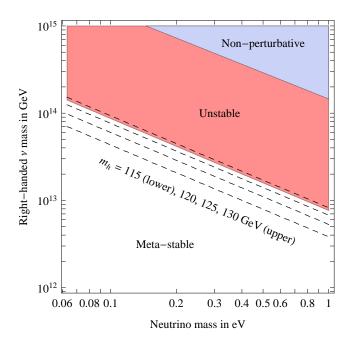


Figure 6: Upper bound at 95% C.L. on the right-handed neutrino mass from vacuum stability (region shaded in red) as a function of the mass of light neutrinos, assumed to be degenerate. The upper region shaded in gray corresponds to non-perturbative right-handed neutrino couplings, $y_{\nu}^2 > 6$.

3 Thermal vacuum decay

If the Universe underwent a period of expansion when the thermal plasma of relativistic degrees of freedom was at high temperature, thermal fluctuations could have caused the decay of the metastable electroweak vacuum [7, 30, 31] by nucleation of bubbles that probe the Higgs instability region. On the other hand, high-temperature effects also modify the Higgs effective potential, with a tendency of making the origin more stable.

Following the calculation in Ref. [32], the requirement that the false vacuum does not decay during the high T stages of the early Universe sets an upper bound on the reheating temperature $T_{\rm RH}$ after inflation once the Higgs mass is fixed. It should be remembered that $T_{\rm RH}$ in fact is not the maximal temperature achieved after inflation. Such maximal temperature occurs after inflation ends and before reheating completes and is given by [33]

$$T_{\text{max}} = \left(\frac{3}{8}\right)^{2/5} \left(\frac{5}{\pi^3}\right)^{1/8} \frac{g_*^{1/8}(T_{\text{RH}})}{g_*^{1/4}(T_{\text{max}})} M_{\text{Pl}}^{1/4} H_{\text{f}}^{1/4} T_{\text{RH}}^{1/2} , \qquad (8)$$

where $g_*(T)$ counts the effective number of degrees of freedom (with a 7/8 prefactor for fermions) with masses $\ll T$ and $H_{\rm f}$ is the Hubble parameter at the end of inflation. The metastability bound on $T_{\rm RH}$ therefore depends on the particular value of $H_{\rm f}$: for a given $T_{\rm RH}$, the value of $T_{\rm max}$ grows with $H_{\rm f}$. Therefore the metastability constraint on $T_{\rm RH}$ will be more stringent for

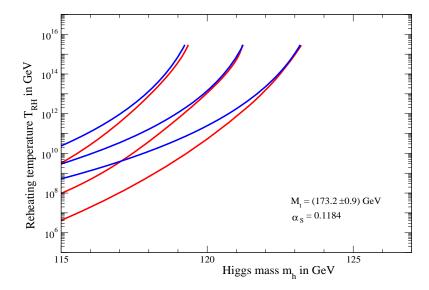


Figure 7: Upper bounds on the reheating temperature $T_{\rm RH}$, as functions of m_h , from sufficient stability of the electroweak vacuum against thermal fluctuations in the hot early Universe for three different values of the top mass (central value and $\pm 1\sigma$). The lower (red) curves are for $H_{\rm f}=10^{14}\,{\rm GeV}$, the upper ones for $H_{\rm f}=[4\pi^3g_*(T_{\rm RH})/45]^{1/2}(T_{\rm RH}^2/M_{\rm Pl})$, which corresponds to the case of instant reheating. We take $\alpha_S(M_Z)=0.1184$. Lowering (increasing) $\alpha_s(M_Z)$ by one standard deviation lowers (increases) the bound on $T_{\rm RH}$ by up to one order of magnitude.

larger values of $H_{\rm f}$ [32].

Figure 7 shows the metastability bound on $T_{\rm RH}$ as a function of the Higgs mass for various values of the top mass and for two choices of the Hubble rate $H_{\rm f}$ at the end of inflation. The lower curves correspond to $H_{\rm f}=10^{14}~{\rm GeV}$ while the upper ones have

$$H_{\rm f} = H_{\rm f}^{\rm min} \equiv [4\pi^3 g_*(T_{\rm RH})/45]^{1/2} (T_{\rm RH}^2/M_{\rm Pl})$$
 (9)

which is the lowest value of $H_{\rm f}$ allowed once it is required that the inflaton energy density $\rho_{\phi} = 3M_{\rm Pl}^2 H_{\rm f}^2/(8\pi)$ is larger than the energy density of a thermal bath with temperature $T_{\rm RH}$. The current observations of the Cosmic Microwave Background (CMB) anisotropies [34] are consistent with a smooth and nearly Gaussian power spectrum of curvature perturbations limiting the contributions to the anisotropies from of tensor modes. This translates into an upper bound of the Hubble rate during inflation given by $H_* < 4 \times 10^{14}$ GeV. Since the Hubble rate during inflation decreases, that is $H_{\rm f} < H_*$, the corresponding maximal upper bound on $T_{\rm RH}$ is $T_{\rm RH} < 2.6 \, [106.75/g_*(T_{\rm RH})]^{1/2} \times 10^{15}$ GeV.

The bound on $T_{\rm RH}$ from thermal metastability gets weaker for smaller values of the top mass or larger values of the Higgs mass since the instability scale becomes higher. Figure 7

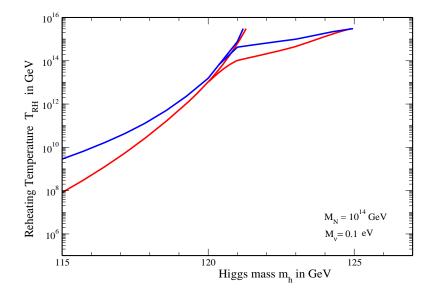


Figure 8: Upper bounds on the reheating temperature $T_{\rm RH}$, as functions of m_h , from sufficient stability of the electroweak vacuum against thermal fluctuations in the hot early Universe, as in fig. 7, but with a seesaw mechanism with $M_N=10^{14}$ GeV, $m_{\nu}=0.1\,{\rm eV}$. As in fig. 7, the lower curves are for $H_{\rm f}=10^{14}$ GeV, the upper ones for instant reheating, and for the central values of m_t and α_s .

shows the thermal metastability scale (blue highest lines), defined as the scale below which the Higgs potential should be modified to avoid thermal decay. For

$$m_h > 121.7 \,\text{GeV} + 2 \,\text{GeV} \left(\frac{m_t - 173.2 \,\text{GeV}}{0.9 \,\text{GeV}}\right) - 0.6 \,\text{GeV} \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3 \,\text{GeV}, \quad (10)$$

the vacuum is sufficiently long-lived even for $T \sim M_{\rm Pl}$, and therefore, the bound on $T_{\rm RH}$ disappears [31]. This is the reason why the lines in fig. 7 stop at some value of m_h . From this figure it is also clear that the bound on $T_{\rm RH}$ is very sensitive on the value of m_t , with the experimental error in m_t being the main source of uncertainty.

3.1 Thermal vacuum decay and leptogenesis

Let us briefly discuss what are the implications of the bound on $T_{\rm RH}$ shown in fig. 7 for the dynamics of the evolution of the Universe. As we mentioned in the introduction, an appealing mechanism for the generation of the baryon asymmetry is leptogenesis in which the asymmetry is produced by the out-of-equilibrium decay of heavy RH neutrinos. Of course, the mechanism works as long as the Universe was ever populated by such heavy states during its evolution. In the most popular version of leptogenesis, the so-called thermal leptogenesis, these heavy states

are produced through thermal scatterings. This sets a lower bound on $T_{\rm RH}$ as a function of M_1 , the mass of the lightest right-handed neutrino [36]. This bound reaches its minimum for $M_1 \sim T_{\rm RH}$, when $T_{\rm RH} > 3 \times 10^9 \, {\rm GeV}$ [35].

The first conclusion we can draw is that hierarchical thermal leptogenesis is not allowed if the Higgs mass turns out to be less than about 120 GeV and the top mass is on the high side of the allowed experimental range.

Moreover, we can conclude that the value of $m_h = 125$ GeV is consistent with thermal leptogenesis and a hierarchical spectrum of RH neutrinos. In fact, for such a value of the Higgs mass, the reheating temperature is comfortably high so that any baryogenesis mechanism would be operative.

As discussed in section 2.2, the Yukawa couplings y_{ν} of the heavy right-handed neutrinos can also modify the instability scale of the Higgs potential [37] and this, in turn, affects the bound on $T_{\rm RH}$. These effects turn out to be important only if the mass of the right-handed neutrinos is sufficiently large, $M_1 \gtrsim (10^{13}-10^{14}) \,\text{GeV}$ [37]. The effect is illustrated in fig. 8, which shows the impact of RH neutrinos with $M_N = 10^{14} \,\text{GeV}$ (with $m_{\nu} = 0.1 \,\text{eV}$) on the bound on the reheating temperature. We conclude that the existence of heavy right-handed neutrinos affect the bounds on $T_{\rm RH}$ for a larger interval of Higgs masses, but only for $T_{\rm RH} > M_1 \gtrsim (10^{13}-10^{14}) \,\text{GeV}$.

We stress that these considerations apply only to the case of hierarchical thermal leptogenesis in the SM, with no new physics present below the scale M_1 . Thermal leptogenesis may indeed occur with almost degenerate RH neutrinos, allowing much lighter values for M_1 (as low as the TeV scale). In such case, no relevant constraint can be derived from stability considerations.

4 Conclusions

We have analysed the stability of the Standard Model vacuum with special emphasis on the hypothesis that the Higgs mass, m_h , is in the following range: 124 GeV $< m_h <$ 126 GeV, as hinted by recent ATLAS and CMS data.

Given the upper bound on the Higgs mass of 127 GeV, we conclude that the Standard Model ground state is very likely to be metastable. In the preferred range of m_h the deeper minimum of the potential occurring at very high energies is sufficiently long-lived compared to the age of the Universe. Full stability is unlikely and would require m_t to be closer to its lower allowed range, as summarized in fig. 3.

The scale where the Higgs potential becomes unstable is very high, around 10^{11} GeV for $m_h = 125$ GeV and central values of m_t ans α_s . As a result, no significant constrains on the reheating temperature are obtained. On the other hand, if the model is extended with the inclusion of heavy RH neutrinos, an upper bound on their masses in the 10^{13} – 10^{14} GeV range

(summarized in fig. 6) can be derived by the requirement that the electroweak vacuum has a lifetime longer than the age of the Universe.

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